Geology

Steady rotation of the Cascade arc

Ray E. Wells and Robert McCaffrey

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Notes

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Ray E. Wells[1] and Robert McCaffrey[2]
[1]U.S. Geological Survey, 345 Middlefield Road, MS 973, Menlo Park, California 94025, USA
[2]Department of Geology, Portland State University, PO Box 751, Portland, Oregon 97207-0751, USA

ABSTRACT

Displacement of the Miocene Cascade volcanic arc (northwestern North America) from the active arc is in the same sense and at nearly the same rate as the present clockwise block motions calculated from GPS velocities in a North American reference frame. Migration of the ancestral arc over the past 16 m.y. can be explained by clockwise rotation of upper-plate blocks at 1.0°/m.y. over a linear melting source moving westward 1–4.5 km/m.y. due to slab rollback. Block motion and slab rollback are in opposite directions in the northern arc, but both are westerly in the southern extensional arc, where rollback may be enhanced by proximity to the edge of the Juan de Fuca slab. Similarities between post–16 Ma arc migration, paleomagnetic rotation, and modern GPS block motions indicate that the secular block motions from decadal GPS can be used to calculate long-term strain rates and earthquake hazards. Northwest-directed Basin and Range extension of 140 km is predicted behind the southern arc since 16 Ma, and 70 km of shortening is predicted in the northern arc. The GPS rotation poles overlie a high-velocity slab of the Siletzia terrane dangling into the mantle beneath Idaho (United States), which may provide an anchor for the rotations.

INTRODUCTION

The Cascade volcanic arc, which extends from British Columbia (Canada) southward into northern California (United States), is the product of subduction of the Juan de Fuca plate beneath North America (Fig. 1A). Its 40 m.y. history is recorded in volcanic and plutonic rocks that are progressively offset clockwise from the modern arc axis. Cascade arc migration is consistent with clockwise rotation of western Oregon determined from paleomagnetism (e.g., Magill and Cox, 1981; Wells, 1990; Wells et al., 1998), although slab rollback or flattening in response to changing slab buoyancy, terrane accretion, or mantle flow regime have all been proposed as possible contributors (e.g., Priest, 1990). Arc rotation occurs when subduction parameters vary along strike, for example, where rollback is locally impeded by collision of buoyant, thickened crust, as in the northern New Zealand or Tonga-Kermadec arcs (Wallace et al., 2005), or where proximity to a slab edge may promote rollback and extension in the overlying plate (Schellart, 2008). Humphreys and Coblentz (2007) suggested that Cascadia slab rollback is a critical geodynamic component permitting westward escape and rotation of the Pacific Northwest.

We examine the rotation of the Cascade arc in light of recent GPS results which show that the Pacific Northwest is still rotating clockwise at up to 2.0°/m.y. (Fig. 1B; McCaffrey et al., 2007, 2013). The progressive offset of the ancient Cascade arc provides an opportunity to examine the utility of GPS for quantifying long-term block-like motions and the relative importance of crustal rotation versus slab rollback in arc evolution. We show that geodetic rates agree with late Cenozoic rates inferred from paleomagnetism and geology, and from that agreement we infer long-term rates of slab rollback and block rotation. We use the GPS-derived poles to reconstruct the Miocene arc at 16 Ma and examine implications for back-arc extension and magmatism, and arc deformation in Cascadia.

GPS VELOCITIES VERSUS GEOLOGIC DISPLACEMENT RATES

Geodetic Rotation Rates Match Paleomagnetic Rates

Paleomagnetic studies show that western Oregon has rotated about a vertical axis at 1.19° ± 0.1°/m.y. for much of Cenozoic time, with the rate decreasing to the north, south,

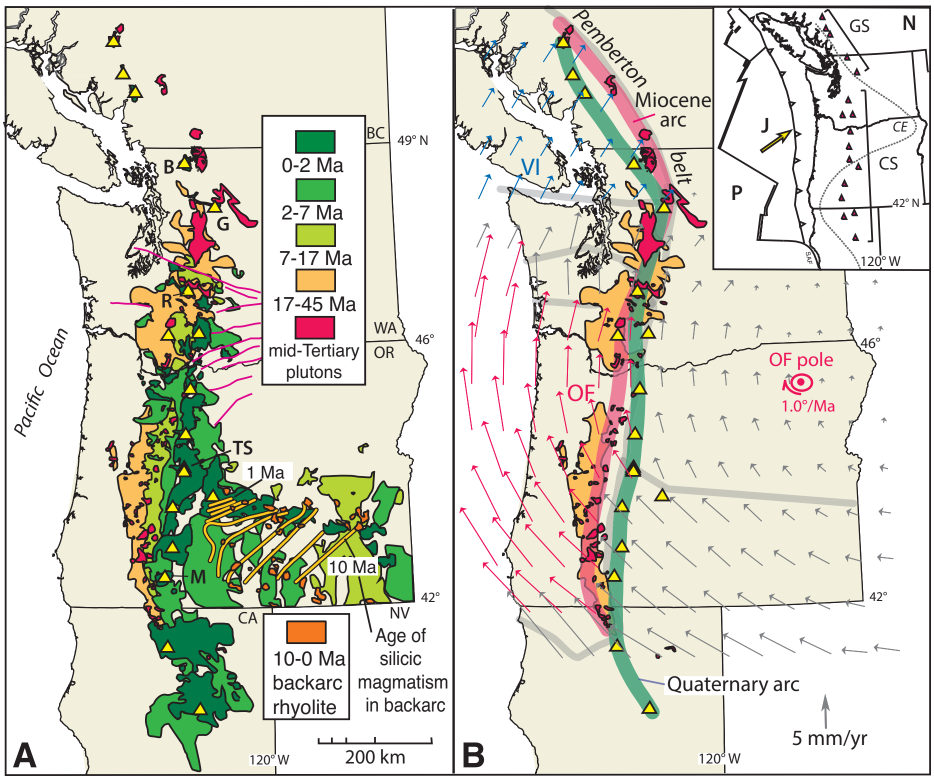

Figure 1. A: Cascade volcanic arc and back-arc ages (northwest North America; Smith, 1993; Sherrod and Smith, 2000; Hildreth, 2007; Massey et al., 2005). Yellow triangles are major Cascade volcanoes: Mount Baker (B), Glacier Peak (G), Mount Rainier (R), Three Sisters (TS), and Mount McLoughlin (M). Red lines show Yakima fold-and-thrust belt. BC—British Columbia; WA—Washington; OR—Oregon; CA—California; NV—Nevada. B: Block velocities (arrows) from GPS (McCaffrey et al., 2007) match sense of offset of ancestral, mostly Miocene Cascade arc plutons (red blobs) from active arc axis (green). Thick gray lines are block boundaries; Oregon forearc block (OF) velocities and pole in red; Vancouver Island block (VI) in blue (pole is off figure). Inset: Pacific (P), Juan de Fuca (J), and North America (N) plates; yellow arrow is convergence direction of Juan de Fuca plate. Garibaldi arc segment (GS), Cascade arc segment (CS) after Hildreth (2007); Mesozoic orocline (dots); and Columbia embayment (CE).

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and east (Fig. 2A). A similar pattern emerges when vertical axis rotation rates are calculated from GPS velocities estimated for the past 15 yr across the Pacific Northwest (Fig. 2B). An east-west profile along the Columbia River (Fig. 2C) shows that GPS rotation rates increase toward the subduction zone (where smaller block rotation occurs) and are nearly identical to the rates calculated from paleomagnetic rotation of 12 Ma and 15 Ma flows of the Columbia River Basalt Group (McCaffrey et al., 2007). The similar rotation rates at vastly different time scales and the great size of the rotating area indicate that the GPS-observed rotation is revealing permanent motions in the upper plate, as opposed to elastic strain from the subduction zone or time-dependent effects of the earthquake cycle.

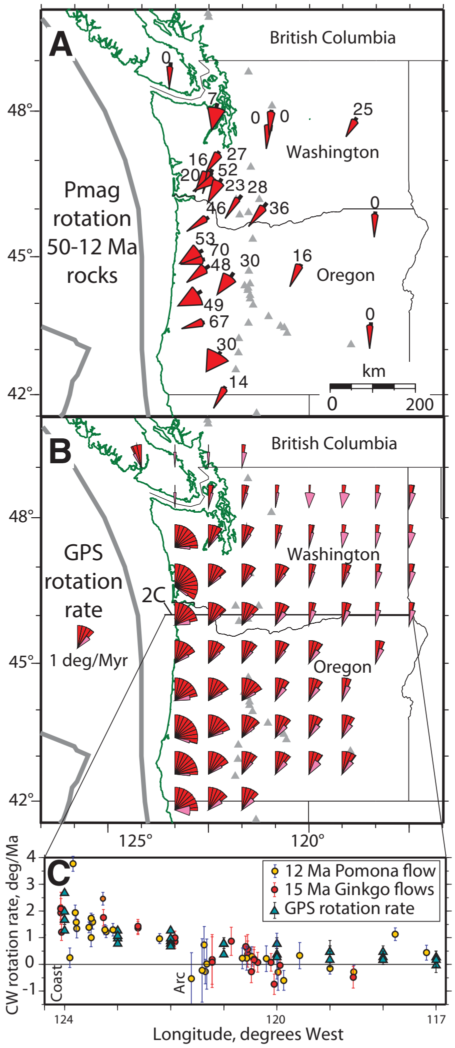

Figure 2. A: Paleomagnetic rotation in degrees, with uncertainties (Wells and Heller, 1988; Irving and Brandon, 1990). B: GPS rotation rates show a similar pattern to that shown in A. C: Clockwise (CW) rotation rates from Columbia River Basalt flows (15–12 Ma) along profile shown in B match rotation rates from GPS shown in B (McCaffrey et al., 2007).

GPS Velocities Are Consistent With Geologic Offset

Because the long-term geologic rotation rates and decadal geodetic rotation rates are essentially the same, we compare the evidence for geologic migration of Cascade arc magmatism over the past 16 m.y. to secular block motions derived from the GPS velocity field after removing the short-term elastic compression due to subduction (McCaffrey et al., 2007, 2013). We suggest that the current surface velocities and their derived poles of rotation acting over millions of years can largely explain the offset of the Miocene arc. In Figure 1B, we superimpose the block velocities (in the North American [NAM] reference frame) calculated from the GPS data on a geologic map of Cascade volcanic and plutonic rocks grouped by age. The axis of the Miocene arc inferred from the distribution of plutons aged 25–9 Ma (du Bray and John, 2011) lies west of the modern arc in Oregon and east of the modern arc in northern Washington State and British Columbia (Hildreth, 2007). Although the pluton distribution is complex in detail and not all plutons are dated, a broad swath through the plutons clearly demonstrates the pattern (Fig. 1B). When compared to the GPS velocity field, the Miocene axis is displaced in a direction consistent with the velocity field, and where modern and ancient arcs are nearly congruent, the GPS velocity is parallel to the arc. Crustal structure and magmatic plumbing can cause shifts in magmatic focus (Hildreth, 2007), but we argue the regional offset is the result of a regional process.

To quantify the ancestral arc offset, we compare the GPS rates to geologic rates of magmatic migration in the direction of the GPS vectors at several localities along the arc. Northeast of Mount Baker (Washington) is a series of calderas and stocks that become progressively older to the northeast (Fig. 3A). They include the Kulshan caldera at 1.1 Ma, the Lake Ann stock at 2.8 Ma, and the Hannegan caldera at 3.7 Ma (Hildreth et al., 2003). At Mount Baker, the shift of magmatic focus is consistent with the observed N42°E plate motion with respect to NAM, with 3.5 mm/yr of the 6.0 mm/yr westward magmatic migration rate explained by block motion. In Oregon, Miocene plutons lay 75–110 ± 15 km northwest of the High Cascade axis in the direction of current plate motion (Fig. 3B). Average geologic displacement rates of the plutons from the present axis since 16 Ma are 3.1 mm/yr at Mount Jefferson and 3.5 mm/yr at Mount McLoughlin (both in Oregon). GPS rates are 4.1 and 7.7 mm/yr, respectively.

Slab Rollback

In both Oregon and Washington, the difference between geologic and GPS rates indicates a westward component of arc migration in NAM of 1–4 mm/yr in addition to block motions calculated from GPS. This additional westward component of arc migration is most easily explained as the result of slab rollback

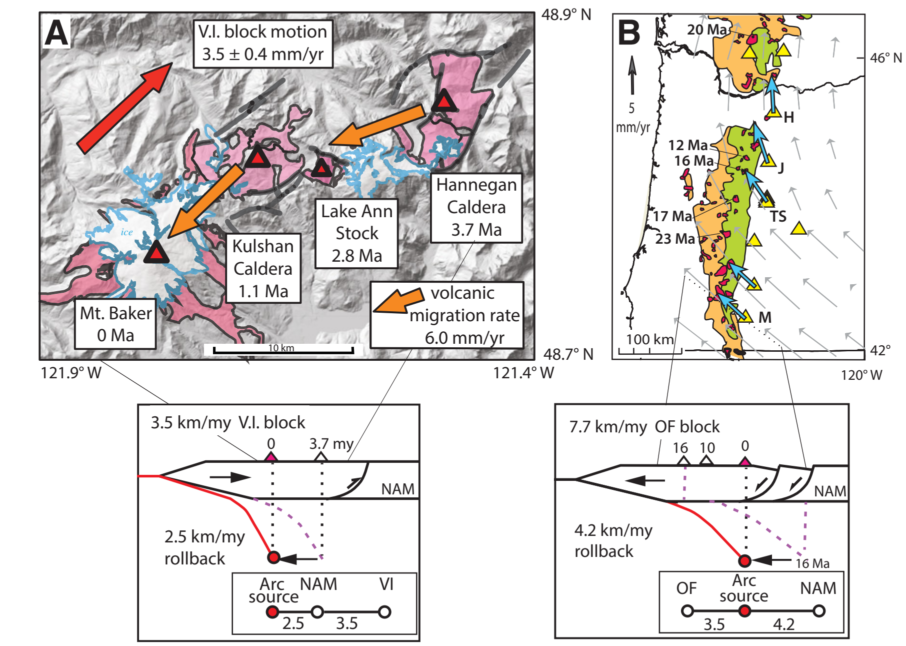

Figure 3. A: Magmatic progression at Mount Baker, Washington, forms linear track on Vancouver Island (VI) block. B: Oregon ancestral arc as in Figure 1; pluton ages from du Bray and John (2011). Blue arrows show inferred geologic displacement of plutons from present axis since 16 Ma. H—Mount Hood; J—Mount Jefferson; TS—Three Sisters; M—Mount McLoughlin. Profiles show slab rollback at Mounts Baker and McLoughlin calculated with respect to North America (NAM). Relative velocities along azimuth of forearc motion, in mm/yr, shown below profiles. OF block—Oregon forearc block.

(i.e., westward motion of slab and trench with respect to NAM; Fig. 3). Our inferred slab rollback component does not appear to be an artifact of the Cascadia subduction zone locking model, as the locking model fits independent vertical and thermal constraints, and the elastic velocities are near zero at the arc (McCaffrey et al., 2007, their figure 10). Modeled transient velocities related to the great Cascadia earthquake of A.D. 1700 also do not match the rollback component (Pollitz et al., 2008). In Washington, the inferred rollback is in the opposite direction of block motion. In Oregon, rollback and block motion are both westerly, but eastward younging of magmatic belts on the rotating forearc block suggests that rollback does not keep up with rotation of the forearc block (Fig. 3B). These observations suggest some decoupling between rollback and rotation. Calculated rollback rates do vary along strike, with largest rates to the south (>4 mm/yr), outboard of the Basin and Range.

CASCADE ARC AND BACK ARC SINCE 16 MA

We used the block rotation poles derived from GPS velocities to restore the Cascade arc to its position at 5, 10, and 16 Ma, matching the magmatic belts in the western Cascades that become younger to the east (Fig. 4). Our flat-earth reconstruction is sufficiently accurate (<0.01 mm/yr) because the poles are very close to the rotating blocks.

The reconstructions show that the older magmatic and plutonic belts in southern Oregon and northern California restore east of the present arc axis at 16 Ma, consistent with their position outboard of the expanding Basin and Range. Restoring the arc to 16 Ma rotates its southern end 140 km to the southeast, equivalent to 100 km of east-west extension in the northern Basin and Range and 100 km of northward motion of the Sierra Nevada block. From geologic data, Colgan and Henry (2009) calculated ~90 km of post–17 Ma, WNW extension across the northern Basin and Range in California and Nevada. McQuarrie and Wernicke (2005) calculated 167 km of post–18 Ma extension across the north-central Basin and Range and 42 km of dextral shear east of the Sierra Nevada since 10 Ma.

The reconstruction predicts post–16 Ma arc-parallel shortening of 70 km between the Columbia River and southern British Columbia, where the Yakima fold-and-thrust belt transects the Washington Cascades (Haugerud and Tabor, 2009; Blakely et al., 2011) (Fig. 1). At 120°W (closer to the pole of rotation), the Yakima fold-and-thrust belt accommodates 25–35 km of arc-parallel shortening (Reidel et al., 1994), similar to the GPS-calculated value of ~30 km (2 mm/yr for 16 Ma). Some shortening may be distributed northward into British Columbia. Substantial shortening in the large gap between Mount Rainier and Glacier Peak volcanoes may have inhibited the rise of magma to the surface.

We restored the Oregon back-arc volcanic units using the GPS poles of rotation for the back-arc blocks, and we examined the rapid northwest migration of rhyolitic magmatism along the High Lava Plains between 10 and 0 Ma (Jordan et al., 2004). The migration rate is 33 mm/yr, slowing to 13 mm/yr in the past 5 m.y. This rate is initially much faster than the GPS rate of the rotating forearc block (~10–13 mm/yr at the Oregon border). Although the direction of the back-arc magmatic progression is in the direction of the moving arc block, the speed is more likely to be related to subduction-driven counterflow above the slab (e.g., Jordan et al., 2004). After 5 Ma, the westward migration of rhyolitic magmatism slows to the forearc block displacement rate, as the counterflow encounters the slower rollback of the Juan de Fuca slab.

IMPLICATIONS FOR ARC PROCESSES AND CORDILLERAN EVOLUTION

Our finding that present-day GPS-derived rotations can largely explain 16 m.y. of arc history implies the present velocity field and driving forces have been relatively stable over latest Cenozoic time. Forearc block rotation has been going on for at least 16 m.y., possibly about similar poles in the back arc. Although mid-Miocene-stage poles (e.g., 16–10 Ma) for the forearc are unknown, we consider the finite rotation about the present GPS-derived rotation pole to provide a reasonable approximation to the actual path of the forearc, given how well the observed geologic offsets are matched.

The position of the active arc in NAM is a function of two processes: plate rotation and an additional westward component we infer is related to slab rollback. Our analysis indicates that the slab is rolling back faster than the motion of North America, consistent with Humphreys and Coblentz' (2007) conclusion that rollback is a critical element of Cordilleran evolution that permits westward escape of the rotating Oregon forearc. But in the northern compressional arc, block rotation and rollback are in opposite directions, indicating that the broader Pacific-NAM dextral shear couple likely drives rotation. In the south, faster rollback and rotation outboard of the expanding

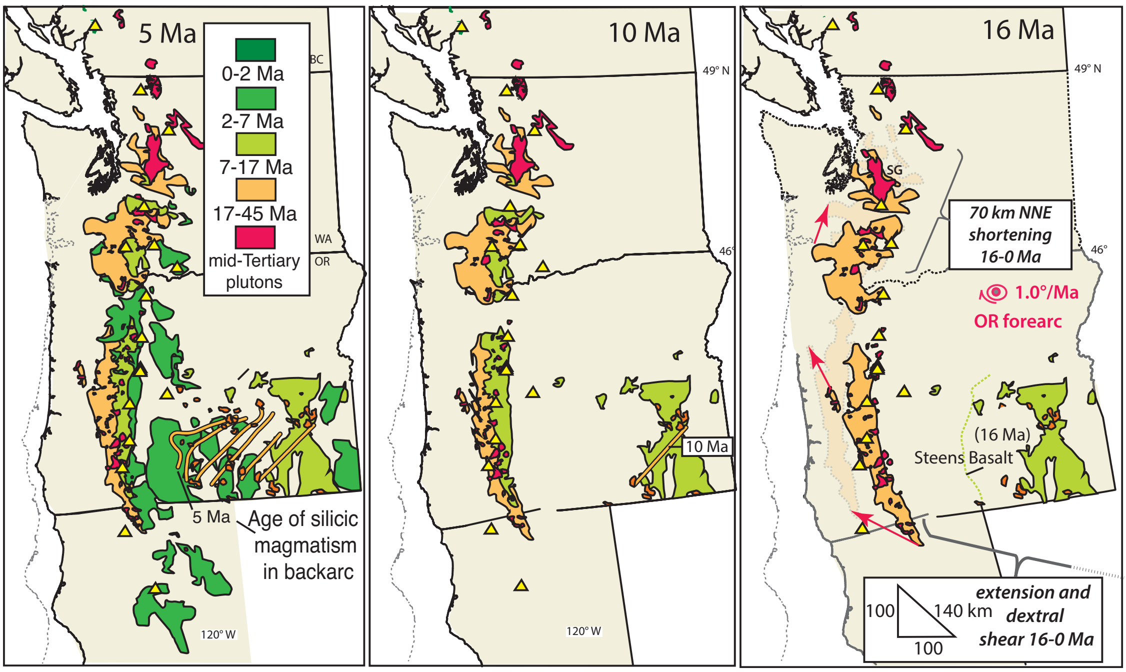

Figure 4. Reconstructions of Cascade arc at 5, 10, and 16 Ma. Present locations of major stratovolcanoes (yellow triangles), coastline (dotted), and 17–45 Ma arc (pale orange) are shown for reference. Oregon (OR) forearc rotation pole and velocities are in red.

Basin and Range may be aided by toroidal flow of the asthenosphere around the southern edge of the sinking Juan de Fuca slab (Zandt and Humphreys, 2008). This is consistent with the global observation that upper-plate extension is favored near slab edges (Schellart, 2008), even when the upper plate (NAM) is moving toward the trench, as in Cascadia. Eastward younging of magmatic belts on the rotating Oregon block indicate that rollback is slower than the block rotation rate, with the arc creating new crust on the trailing edge of the migrating forearc block. Thus, broad dextral shear (i.e., the push from the Sierra Nevada block) must also be an important driving force for rotation of the Oregon forearc.

In contrast to some rotating circum-Pacific arcs, Cascadia lacks an active collision zone, where buoyant crust entering the subduction zone acts as a pivot for arc rotation (Wallace et al., 2005). Cascadia's rotation poles lie near the apex of the Columbia embayment, which is in part filled by Siletzia, an oceanic plateau accreted to North America at ca. 50 Ma (Fig. 1B). McCaffrey et al. (2013) noted the deep root under the Idaho batholith and suggested it may provide a pivot for Pacific Northwest rotation. The high-velocity root dangling into the mantle beneath Idaho may actually be part of the accreted Siletz terrane (Schmandt and Humphreys, 2011), and it may resist motion of the upper plate over the mantle. Although no longer colliding with the continent, Siletzia may still exert some control on Cascadia rotation.

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